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The plasma plume from a 200 W Hall Effect Thruster fueled by iodine vapor was analyzed. The plasma source included a laboratory propellant feed system and a laboratory model Hall thruster powered by a breadboard power processing unit. The hollow cathode was fed with xenon. The distribution of iodine ions was measured with an ExB probe, an electrostatic analyzer (ESA), and a combined ESA/ExB probe. The distribution of xenon ions was also measured. Multiply charge species were detected with both iodine and xenon. Significant populations of diatomic iodine ions were also detected. The dimer fraction was found to vary with operating conditions and angular distance from the beam centroid. The greatest populations of high energy dimers were observed at lower discharge current, and at angles of 30-50 degrees from the beam centroid. At one operating condition, the high energy dimer fraction was approximately 20% by mass in this region. Significant dimer fractions could increase thrust to power by useful amounts at the cost of some overall efficiency.

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Iodine Plasma Species Measurements in a Hall Effect Thruster Plume

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AIAA Paper 2013-XXXX

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Abstract

- The plasma plume from a 200 W Hall Effect Thruster fueled by iodine vapor was analyzed.
- The plasma source included a laboratory propellant feed system and a laboratory model Hall thruster powered by a breadboard power processing unit.
- The distribution of iodine ions was measured with an ExB probe, an electrostatic analyzer (ESA), and a combined ESA/ExB probe.
- Results:
  - Multiply charged species were detected
  - Significant populations of diatomic iodine ions were detected.
  - The dimer fraction was found to vary with operating conditions and angular distance from the beam centroid.
  - The greatest populations of high energy dimers were observed at lower discharge current, and at angles of 30-50 degrees from the beam centroid.
- Dimers could increase thrust to power by useful amounts at the cost of some overall efficiency.

Outline

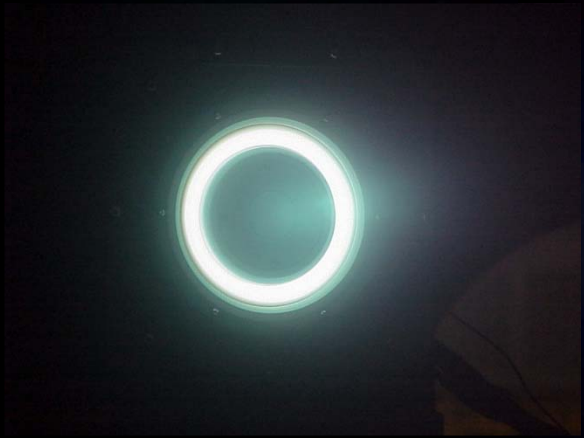
- Background on Iodine Hall Thrusters
- Apparatus and Procedure
- Experimental Data
- Discussion and Implications
- Conclusions

HET Propellants at Busek

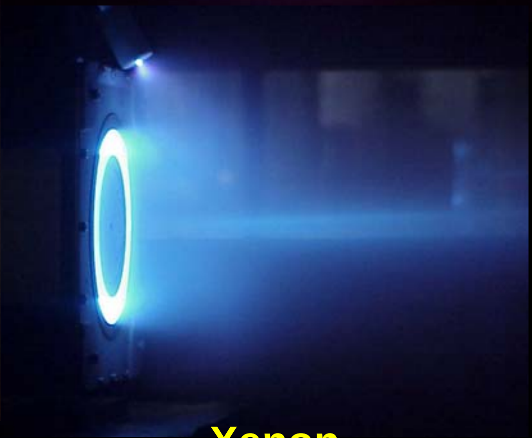
Magnesium
High Isp

Zinc
High Storage Density

Krypton
Alternative Noble Gas



Iodine
Replacement for Xe



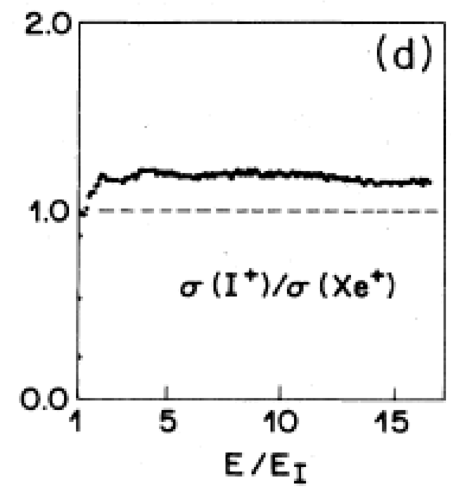
Xenon
SOTA Propellant

Bismuth
High Thrust to Power

Iodine Propellant

- Iodine is an attractive alternative to Xe
  - Easy to ionize
  - Measured thrust, specific impulse, and anode efficiency similar to values obtained with Xe at similar operating conditions
  - Lower beam divergence than Xe
- High density
  - Stores at 2-3 times density of Xe
  - Modest heating to generate gas (sublimation)
- Low feed system pressure
  - Tank pressure is 1000 times lower than Xe
- Passive long term storage
  - I_2 stores in the solid phase
  - No temperature control for inactive system
- Low cost
  - Depends on market, purity
- Easy to pump in test facilities
  - High power ground demonstrations feasible

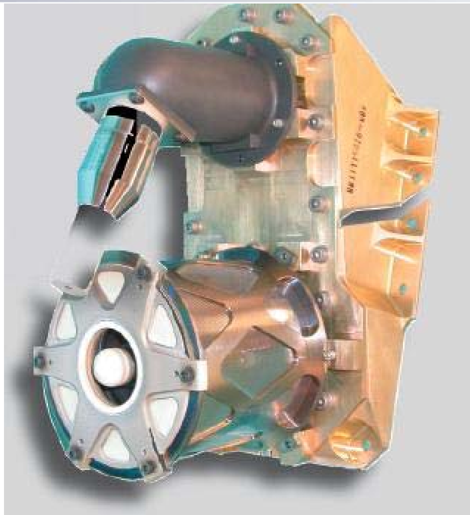
Relative size of ionization cross section

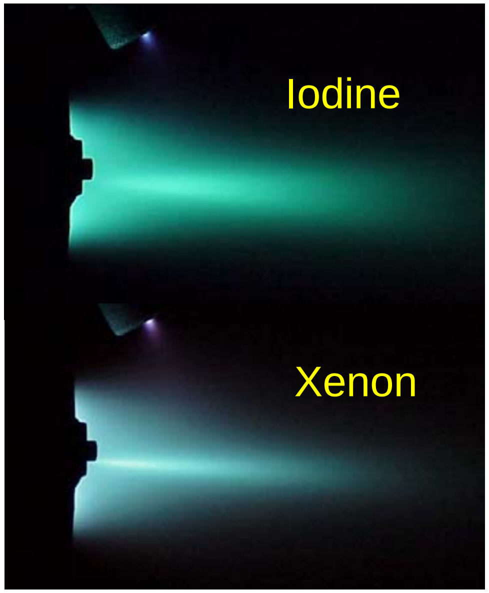


Element	I	Xe
Atomic Mass	126.9	131.3
Ionization Properties (monatomic)		
First Ionization Potential (eV)	10.5	12.1
Peak Cross Section (10^{-16} cm^2)	6.0	4.8
Storage and Handling Properties		
Storage density (gm/cm^3) near room temp.	4.9	1.6*
Melting Point (^oC)	113.7	-112
Boiling Point at 10 Pa (^oC)	9	-181
*14 Mpa, 50 C (NIST Database)		

BHT-200 Flowing Iodine (2010)

- Apparatus
  - BHT-200 Thruster & cathode (flight models)
  - Breadboard PPU
  - Custom propellant feed system
- Procedures
  - Preheat thruster with Xe discharge
  - Measure thrust, plume current with I2 and Xe
  - Measure species (ExB, beam centroid, one condition)
- Results
  - Efficiency with I_2 and Xe close at most conditions
    - Superior to Xe at highest power
  - At same voltage, thrust to power (T/P) usually slightly higher but Isp slightly lower with I_2
  - Much lower tank pressure with I_2
  - Plume divergence lower with I_2
  - Dimers (I_2^+) measured at beam centroid (a few %)





What is the Composition of the Iodine Plume?

- Iodine plasma discharge more complicated than Xe discharge
- What processes need to be included when modeling the discharge and plume?
- How might heavy species impact performance?

Inputs: e, I_2

Process	Reactions
Elastic & Inelastic Scattering	$e + I \rightarrow 2e + I^{+}$ (Basic Xe physics)
	$e + I \rightarrow 3e + I^{2+}$ (Basic Xe physics)
	$e + I_2 \rightarrow 2e + I_2^{+}$
	$e + I_2 \rightarrow 3e + I_2^{2+}$
Dissociation	$e + I_2 \rightarrow e + I + I$
	$e + I_2 \rightarrow 2e + I + I^{+}$
	$e + I_2 \rightarrow 3e + I^{+} + I^{+}$
Electron Attachment (Negative Ions)	$e + I \rightarrow I^{-}$
	$e + I_2 \rightarrow I_2^{-}$
	$e + I_2 \rightarrow I^{-} + I$
Charge Transfer	$I + I^{+} \rightarrow I^{+} + I$ (Basic Xe physics)
	$I_2 + I^{+} \rightarrow I_2^{+} + I$
Recombination	$e + I^{+} \rightarrow I$ (Basic Xe physics)

Basic Xe physics

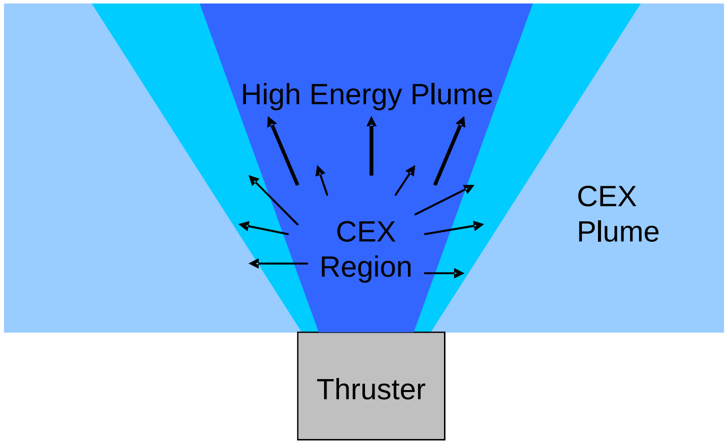
Outputs: e; I, I_2; I^{+}, I_2^{+}, I^{2+}; I^{-}, I_2^{-}

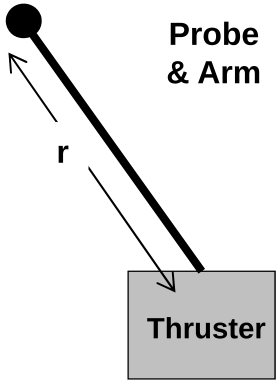
Apparatus

- System Hardware
  - BHT-200 Thruster
    - Experimental version
    - Not identical to flight model
  - BHC-1500 Cathode
    - Flight design
  - BPU-600 PPU
    - Breadboard of flight model
  - Custom propellant feed system
    - Developed at Busek
- Test Hardware
  - Vacuum test facility (6' diameter)
  - Faraday probe (MIT)
  - ESA, ExB, ESA/ExB Probes (Plasma Controls)
  - Rotary probe arm (about thruster exit plane)

Procedure

- Survey plume with Faraday probe
- Measure total species currents with ExB probe
- Measure energy distributions with ESA probe
- Measure high energy species with ESA/ExB probe
- Analyze data





Results - Plume Current

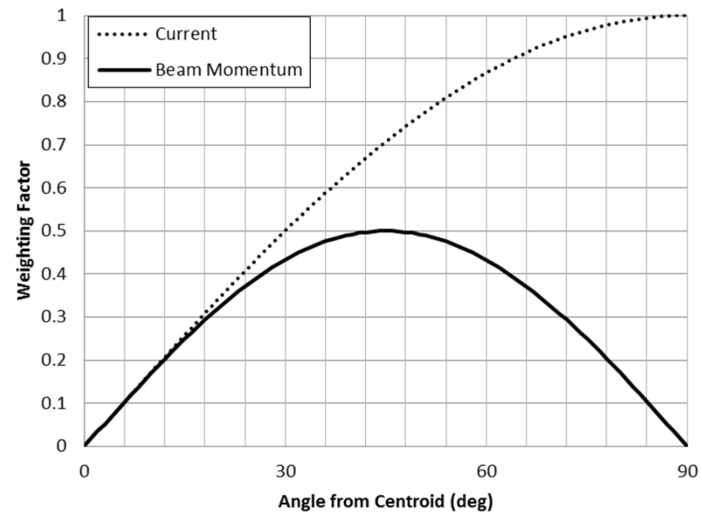
- Probe measures current density vs. angle
- Current vs. angle
  - Integrate j(θ) sin(θ)

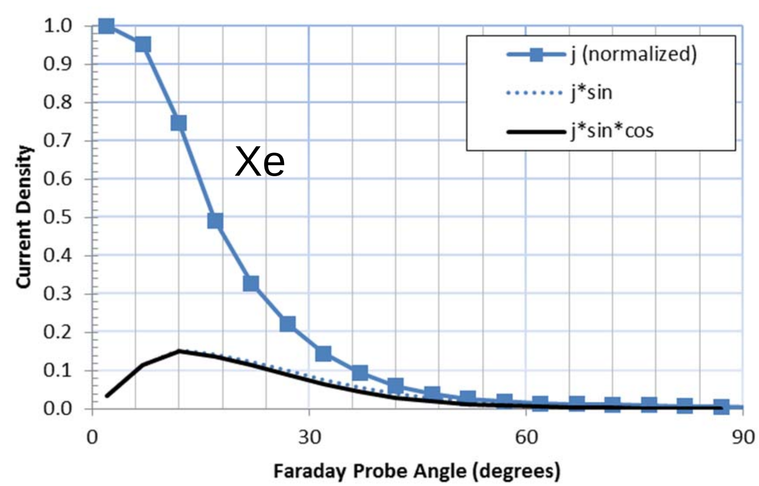
$$I_b = 2\pi r^2 \int_0^{\pi/2} j(\theta)\sin(\theta)d\theta$$

- Axial momentum vs. angle (est.)
  - Integrate j(θ)sin(θ)cos(θ)
  - Trig multiplier peaks at 45º

$$F_t = \frac{2\pi r^2 \int_0^{\pi/2} j(\theta)\sin(\theta)\cos(\theta)d\theta}{I_b}$$

- Significant momentum at θ>20º
- Composition away from centroid matters





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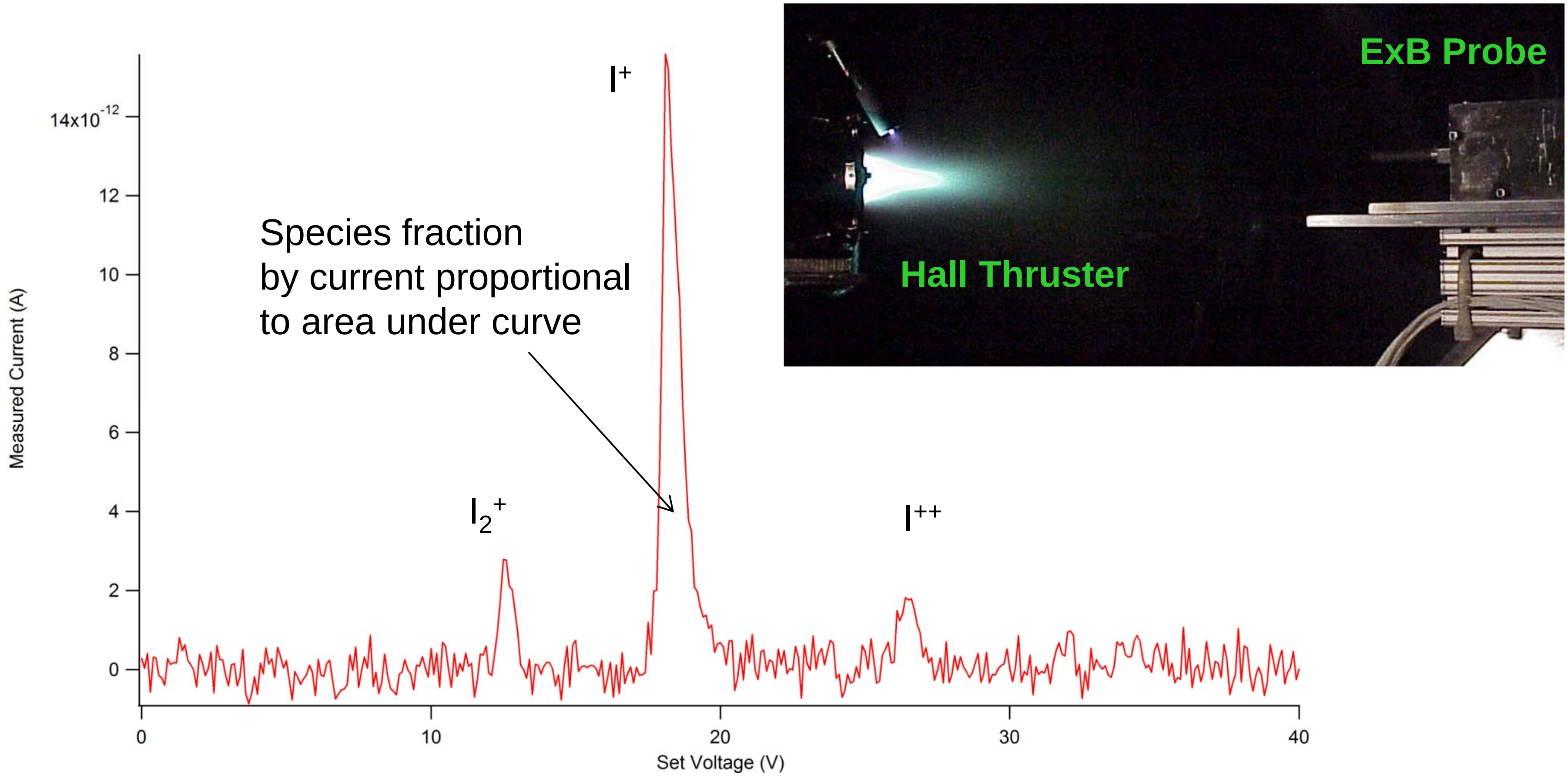
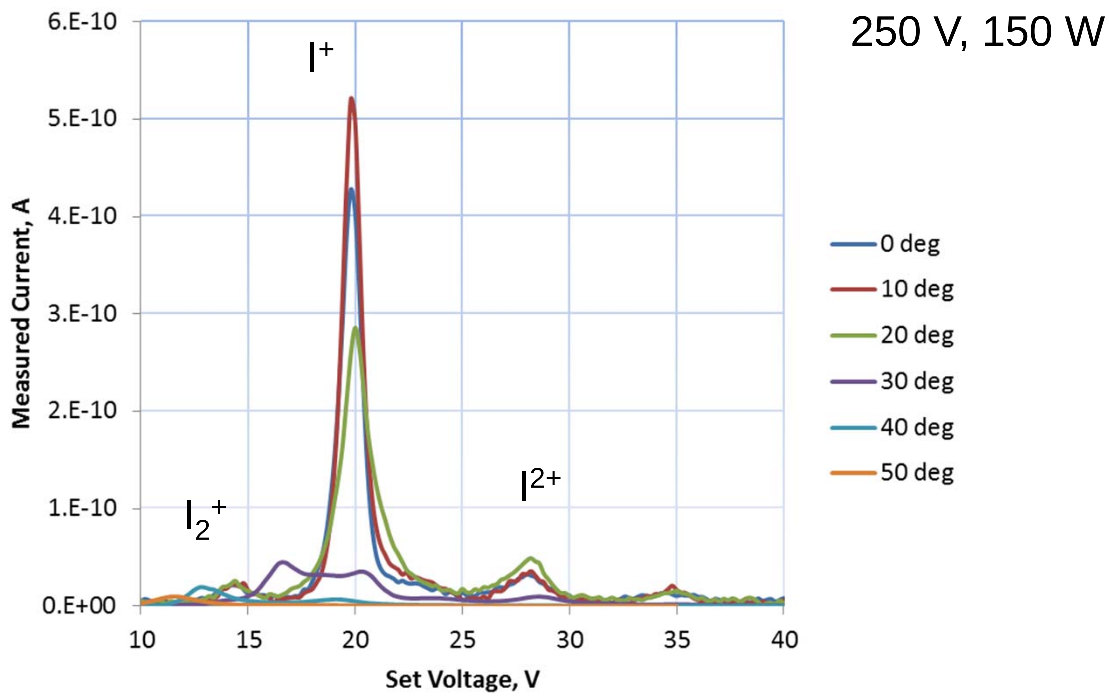
Species Analysis (ESA/ExB)

- ExB probe measures current
- Species fractions are proportional to the area under the curve



Results - Iodine ExB

- ExB sweeps taken at a wide variety of operating conditions, angles
- I_2^+ signals clearly observed in many sweeps
- Issue: ExB sweeps do not resolve energy or momentum carried by species
  - Some or all of the dimers could be low energy



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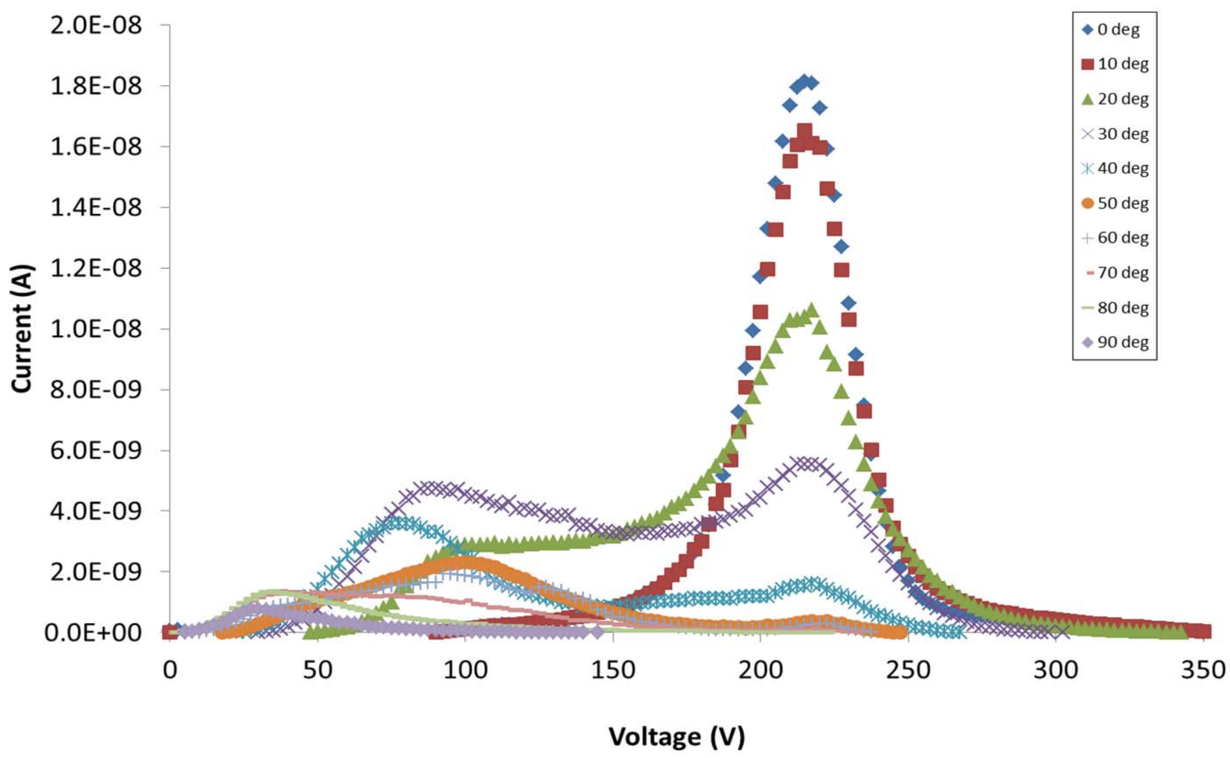
Results - Iodine ESA

- ESA sweeps taken at same operating conditions, angles
- Energy distribution varies with position
  - Mostly low energy CEX in wings
- For effect of dimers on thrust, want to limit analysis to <u>high energy</u> populations



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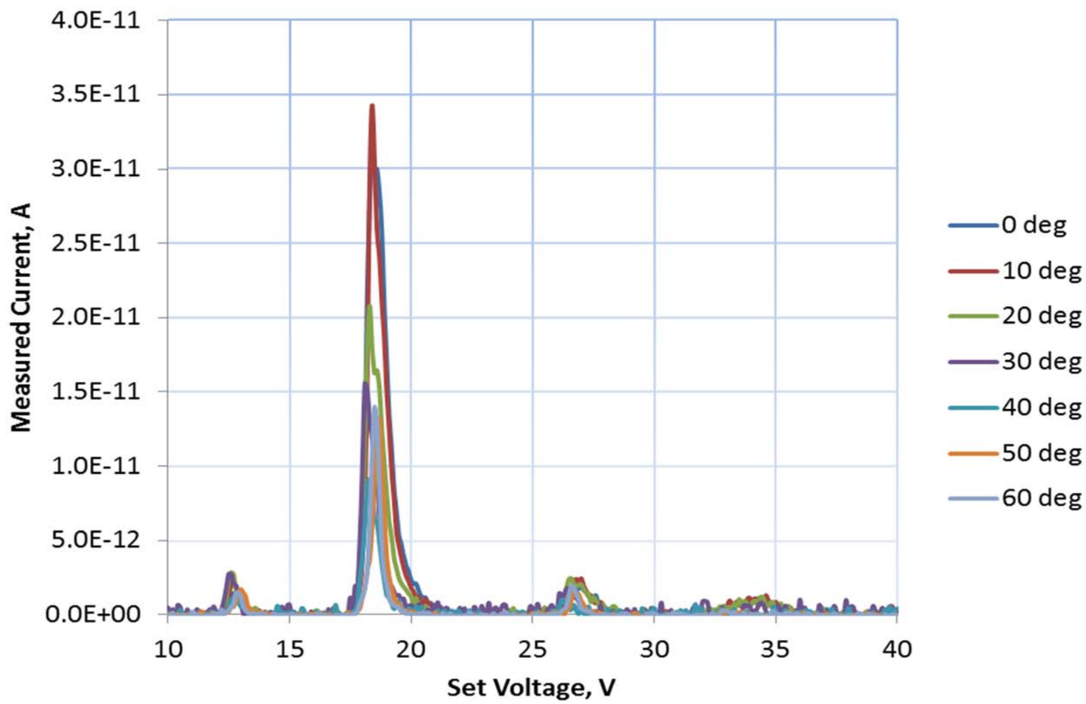
Results – Iodine ESA/ExB

- Combined probe selects only high energy ions
  - At 250 V, 150 W, 30 degrees, >20% of the high energy beam by mass comes from dimers

250 V, 150 W High energy peak



				Current	Mass	Molar
Angle (deg)	Species	Mass	Charge	f	g	h
0	I_2^+	2	1	0.02	0.04	0.02
0	I^+	1	1	0.92	0.93	0.95
0	I^{2+}	1	2	0.05	0.03	0.03
0	I^{3+}	1	3	0.00	0.00	0.00
10	I_2^+	2	1	0.04	0.08	0.04
10	I^+	1	1	0.86	0.87	0.91
10	I^{2+}	1	2	0.09	0.05	0.05
10	I^{3+}	1	3	0.01	0.00	0.00
20	I_2^+	2	1	0.07	0.14	0.07
20	I^+	1	1	0.80	0.80	0.86
20	I^{2+}	1	2	0.13	0.07	0.07
20	I^{3+}	1	3	0.00	0.00	0.00
30	I_2^+	2	1	0.12	0.22	0.12
30	I^+	1	1	0.76	0.72	0.81
30	I^{2+}	1	2	0.12	0.06	0.06
30	I^{3+}	1	3	0.00	0.00	0.00
40	I_2^+	2	1	0.10	0.18	0.10
40	I^+	1	1	0.85	0.80	0.87
40	I^{2+}	1	2	0.05	0.02	0.03
50	I_2^+	2	1	0.11	0.20	0.11
50	I^+	1	1	0.79	0.75	0.83
50	I^{2+}	1	2	0.11	0.05	0.06
60	I_2^+	2	1	0.08	0.17	0.09
60	I^+	1	1	0.80	0.78	0.85
60	I^{2+}	1	2	0.12	0.06	0.06

Species Fraction Definitions

- Area A = peak height x width @ half maximum
- f: current fractions
  - Collected by ExB
- h: number fractions
  - Factor out charge
  - I^{++} has twice as much
- g: mass fractions
  - Factor in mass
  - Dimers weigh twice as much

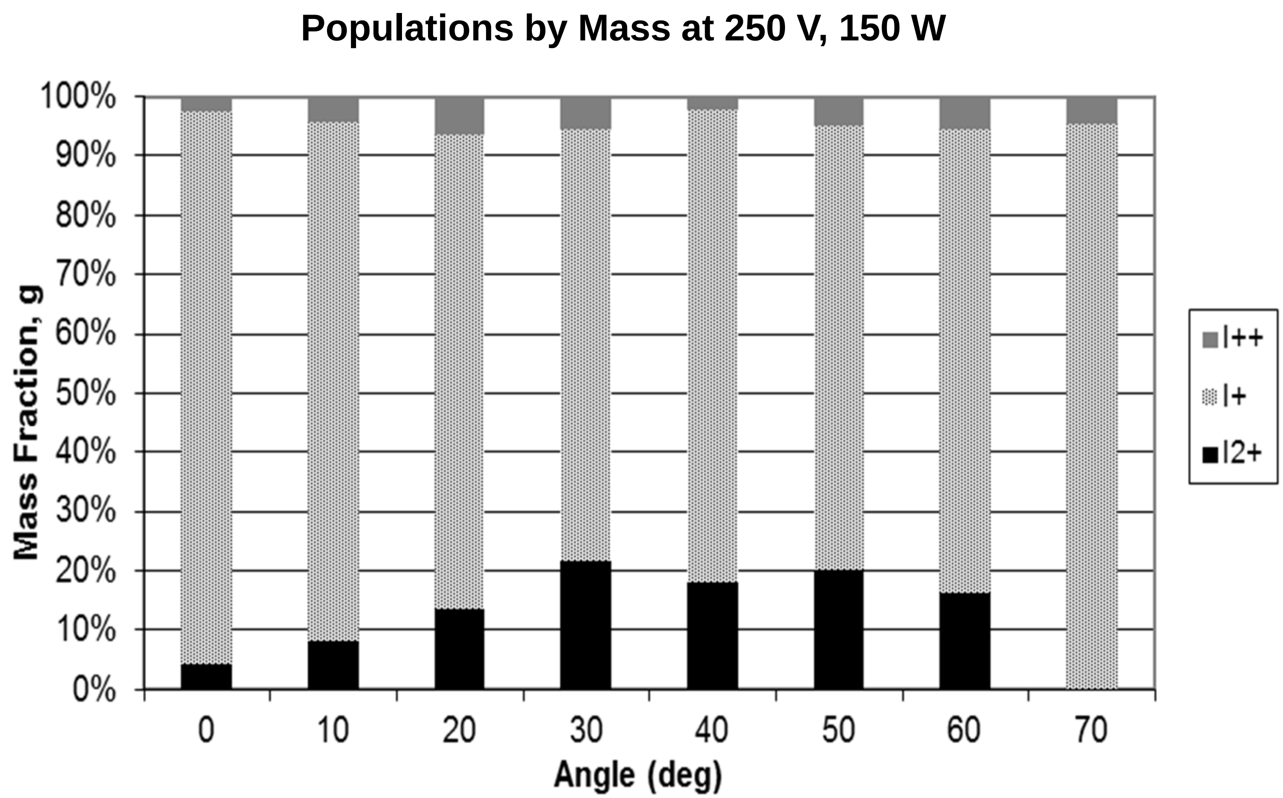
$$f_k = \frac{A_k}{\sum_k A_k}$$

$$h_k = \frac{A_k / q_k}{\sum_k A_k / q_k}$$

$$g_k = \frac{A_k M_k / q_k}{\sum_k A_k M_k / q_k}$$

Results – High Energy Iodine Species

- Measured fraction of beam that is dimers can be very significant
  - Fraction by mass (function g) is 20% at some locations and operating conditions



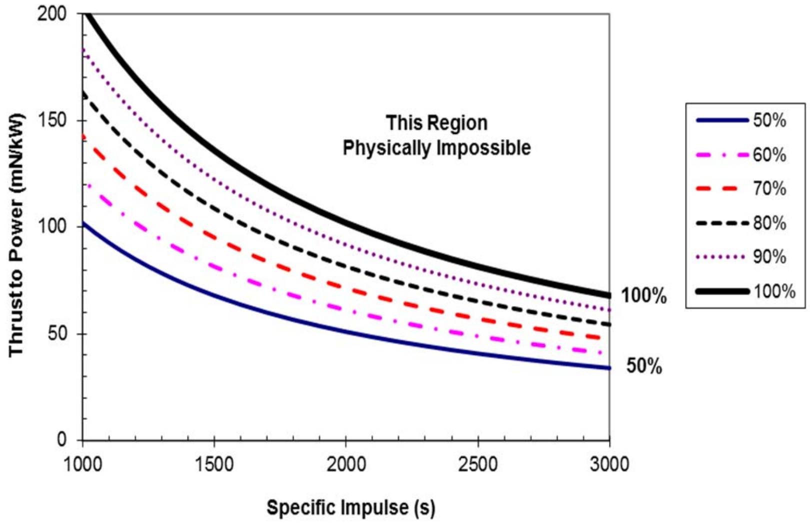
What Effect Might Dimers Have Upon Performance?

- Thrust
  - Thrust is sum of species

$$F = \sum_k \dot{m}_k < v_{k,z} >.$$

  - Ion voltage, mass, charge determine ion velocity

$$v = \sqrt{\frac{2q\Delta\Phi}{M}}$$



- Specific Impulse
  - Determined by thrust and mass flow
- Efficiency
  - Determined by thrust, mass flow, power
- Thrust to power
  - Determined by efficiency, specific impulse
- Can estimate effect of species distributions upon these parameters

$$I_{sp} = F / \dot{m} g_0 = \overline{v} / g_0$$

$$\eta = \frac{F}{P}\frac{I_{sp} g_0}{2} = \frac{F^2}{2\dot{m}P}$$

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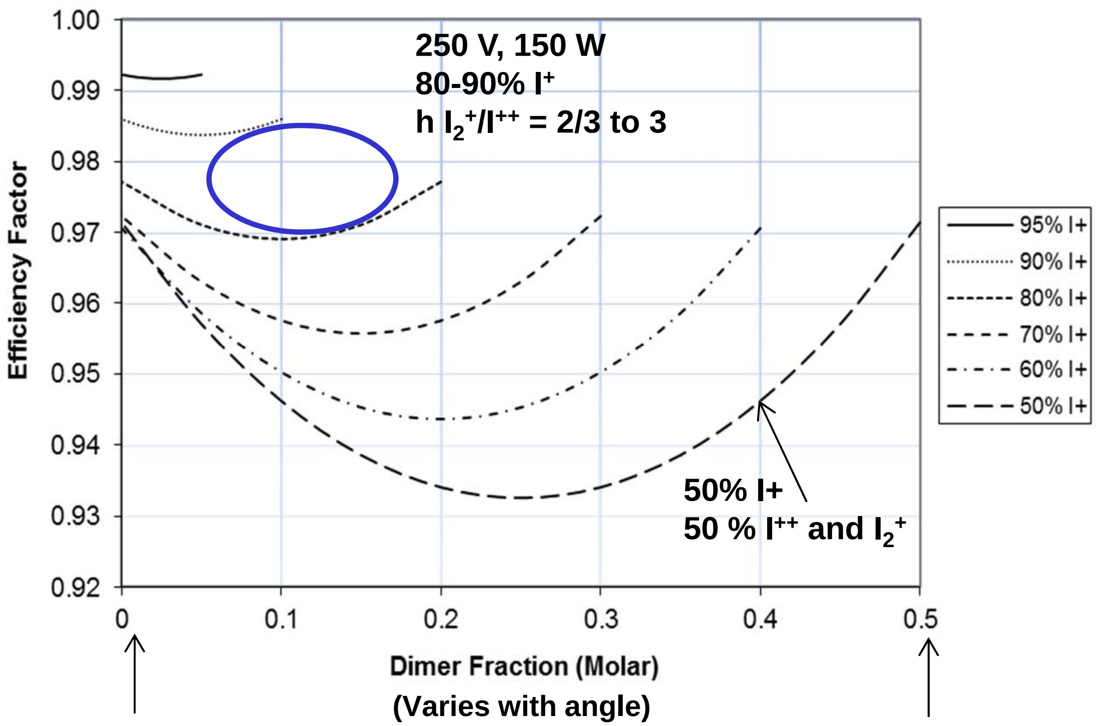
Discussion - Efficiency Factor (Theory)

$$\eta_s \propto \frac{(\sum_k h_k M_k v_k)^2}{\sum_k h_k M_k \sum_k h_k q_k}$$

$$\eta = \frac{F^2}{2\dot{m}P}$$

Efficiency factor (polydispersivity) with respect to a purely monatomic beam

The presence of multiple species does not mean the thruster will be inefficient (though there is an efficiency loss)



No dimers

No doubly charged

$\eta_s = 0.98$
$\eta = 50\% \rightarrow 49\%$

$\eta_s = 0.94$
$\eta = 50\% \rightarrow 47\%$

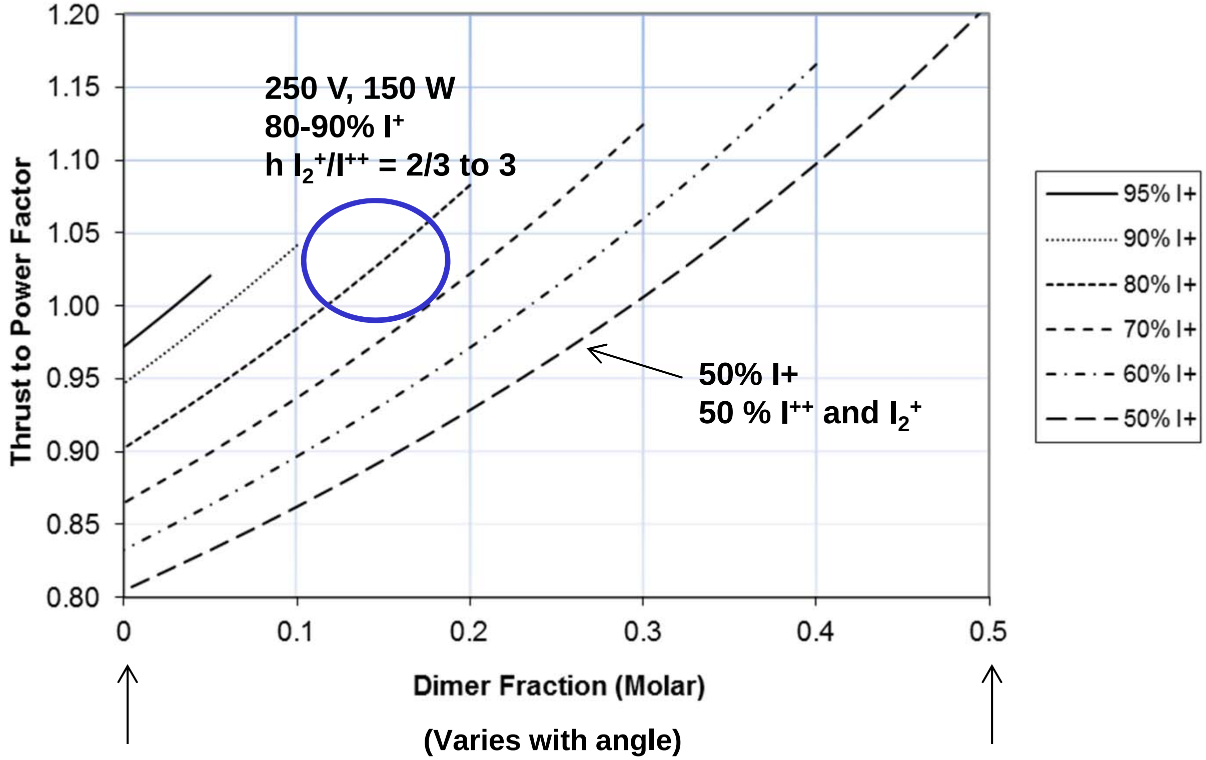
Starting point
Is <u>not</u> $\eta_s = 1.0$
(Xe^{++})

Discussion - Thrust to Power Factor (Theory)

$$\frac{T}{P} \propto \frac{\sum_k h_k M_k v_k}{\sum_k h_k q_k}$$

T/P factor is with respect to a purely monatomic beam

Dimers have the potential to increase T/P by a significant amount (but you need a lot to make a really big difference)



No dimers

No doubly charged

Results vary with Operating Conditions, Position

- Dimer fraction varies significantly with operating conditions.
  - Largest when the current is low and the discharge is rarified.
  - Highest fractions are observed at 250 V and 150 W, where I=0.6 A.
  - Relatively large, localized populations are also found at 0.71 and 0.8 A.
- Dimer fraction is larger off axis than in the center of the beam
  - But momentum also peaks away from the centroid
- Dimers are present in sufficient numbers to measurably increase T/P

Current Fractions

		Discharge Conditions							
		150	200	250	250	300	350	350	[V]
Angle [deg]	Species	1.00	1.00	0.60	0.80	0.80	0.71	1.00	[A]
		150	200	150	200	240	250	350	[W]
0	I_2^+			0.02	0.01		0.01		
0	I^+	0.53	1.00	0.92	0.95	0.93	0.94	0.96	
0	I^{2+}	0.47	0.00	0.05	0.04	0.07	0.05	0.04	
0	I^{3+}			0.00	0.00	0.00			
10	I_2^+			0.04	0.03	0.02	0.02		
10	I^+	0.98	0.83	0.86	0.82	0.83	0.90	0.88	
10	I^{2+}	0.02	0.14	0.09	0.08	0.11	0.08	0.12	
10	I^{3+}		0.03	0.01	0.07	0.05			
20	I_2^+			0.07	0.02	0.02	0.06	0.00	
20	I^+	0.99	0.40	0.80	0.85	0.82	0.77	0.86	
20	I^{2+}	0.01	0.60	0.13	0.13	0.15	0.18	0.13	
20	I^{3+}			0.00	0.01	0.00			
30	I_2^+			0.12	0.00	0.03		0.02	
30	I^+	1.00	0.85	0.76	0.95	0.77	0.86	0.79	
30	I^{2+}		0.15	0.12	0.00	0.18	0.14	0.19	
30	I^{3+}			0.00	0.05	0.03			
40	I_2^+			0.10	0.00	0.05	0.01	0.02	
40	I^+	1.00	0.85	0.85	0.90	0.76	0.87	0.75	
40	I^{2+}		0.15	0.05	0.10	0.19	0.13	0.23	
50	I_2^+			0.11	0.00	0.04	0.01	0.00	
50	I^+	1.00	1.00	0.79	0.91	0.82	0.90	0.84	
50	I^{2+}			0.11	0.09	0.14	0.09	0.16	
60	I_2^+			0.08	0.06	0.04	0.08	0.00	
60	I^+		1.00	0.80	0.81	0.92	0.81	0.83	
60	I^{2+}			0.12	0.13	0.04	0.12	0.17	

Conclusions

- Iodine vapor has been shown to be an attractive replacement for Xe for typical missions (past work)
  - Thrusters characterized at power levels from 100 W to 10 kW
  - Measured thrust, specific impulse, and anode efficiency similar to values obtained with Xe at similar operating conditions
  - Beam divergence lower with iodine
- Plume of experimental BHT-200 measured with multiple instruments
  - Faraday probe → plume current
  - ExB probe → species populations across all energies
  - Electrostatic analyzer (ESA) → ion energies across all populations
  - ESA/ExB → species populations at selected energies and positions
- Results
  - Significant populations of molecular iodine present at some locations and operating conditions
  - Should be included in models of the discharge and plume
  - Populations large enough to measurably affect performance
  - Future work is required

Potential Applications for Iodine

- Low power (200 W and similar)
  - Compact, low mass propulsion system for small S/C
  - De-orbit systems

- Medium power (1 to 5 kW)
  - Geo-stationary satellites
    - GTO to GEO transfers
    - Station-keeping
  - Payload delivery systems based on ESPA or similar
  - Interplanetary probes
    - NASA Flagship, Frontier, Discovery class missions to Asteroids, comets, dwarf planets, outer planets

- High power (10 kW and above)
  - High power electric upper stages
  - NASA SEP demonstration
  - Missions to the moon, Mars, asteroids, supporting human exploration

Acknowledgements

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- Additional testing supported by the USAF, NASA, and ULA

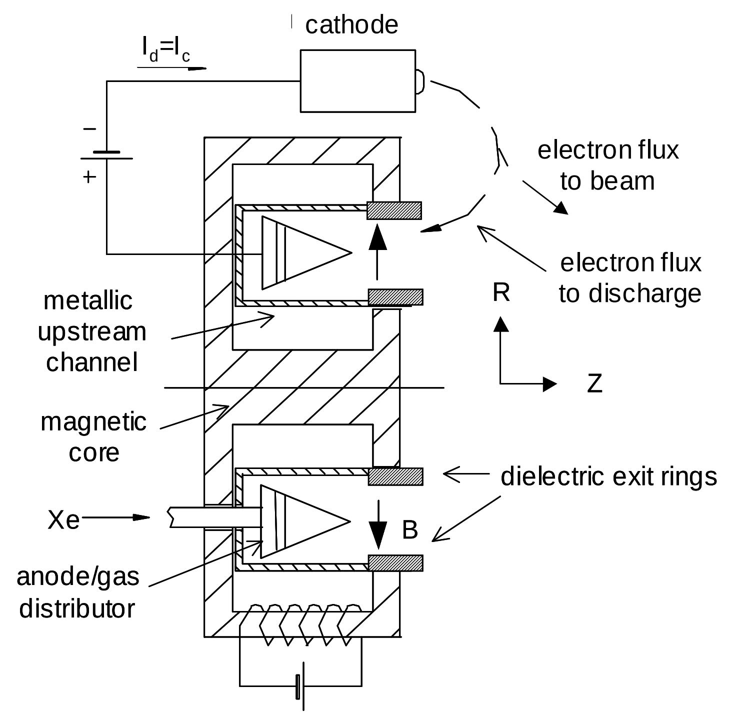
Backup Slides

BHT-8000 Operating on Iodine

Hall Effect Thrusters (HETs)

- Form of electric propulsion used for in-space maneuvers
  - Simple
  - Efficient
  - High thrust density
  - Low cost
- Plasma is ionized in an electron-impact cascade and accelerated by an applied electric field
- Beam neutralized by a cathode

- Typical propellant is xenon
  - All known flight thrusters
- Many potential alternatives

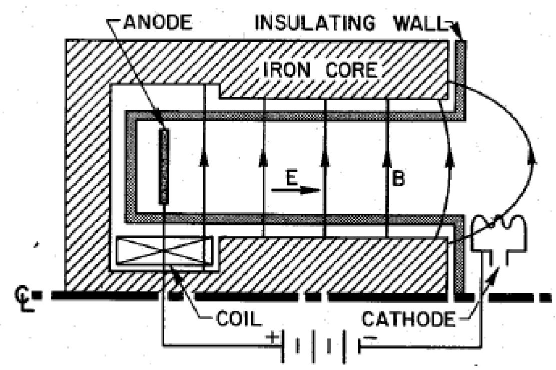


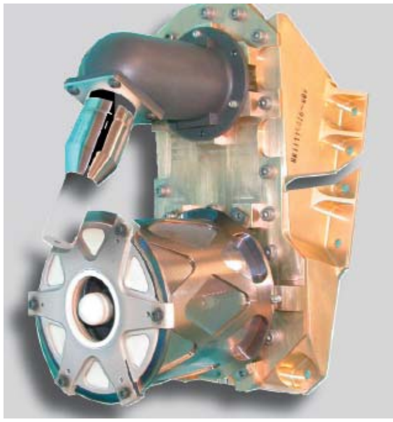
Axisymmetric Hall thruster

History of Hall Effect Thrusters

- 1962 First Hall Effect Thrusters (US)
- 1963 First Soviet thrusters (Morozov, USSR)
- 1971 First HET in space (USSR, Meteor-18)
- 1982 SPT-100 and SPT-70 introduced (USSR)
- 1991 Soviet HETs reintroduced to West
- 1993 Busek begins Hall thruster development
  -- All US owned technology
- 1998 D-55 (USSR) launched on STEX (US)
- 2003 SMART-1 mission (ESA) beyond GEO
  -- French thruster based on Russian technology
- 2006 Busek BHT-200 launched on TacSat-2 (US)
  -- First US Hall thruster in Space
- 2010 Aerojet BPT-4000 launched on AEHF (US)
  -- Licensed Busek technology
- 2010 BHT-200 demonstrated on iodine propellant (US)

Axisymmetric Hall thruster of United Aircraft Corporation (1962)



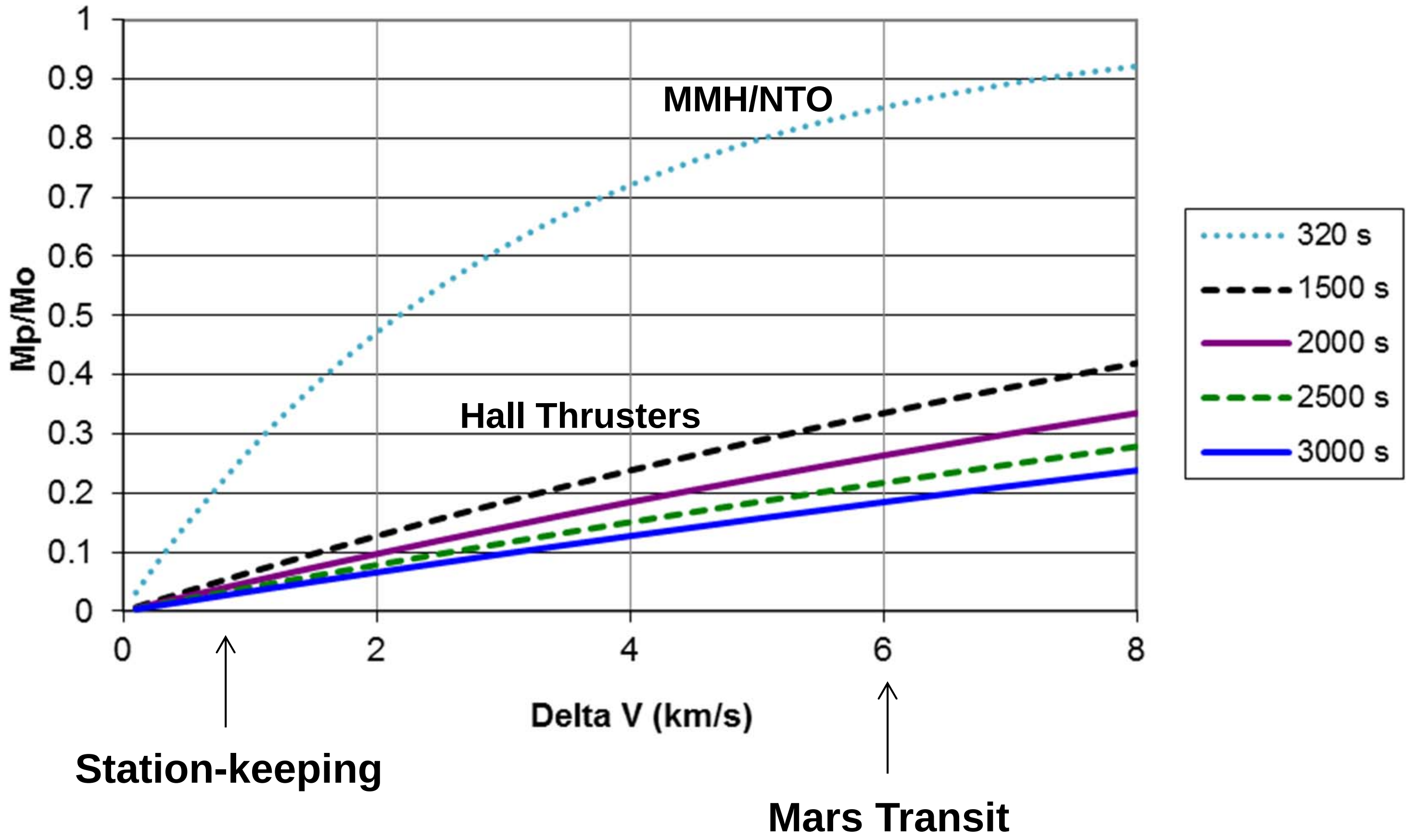


Busek BHT-200
First US thruster in Space

The Rocket Equation

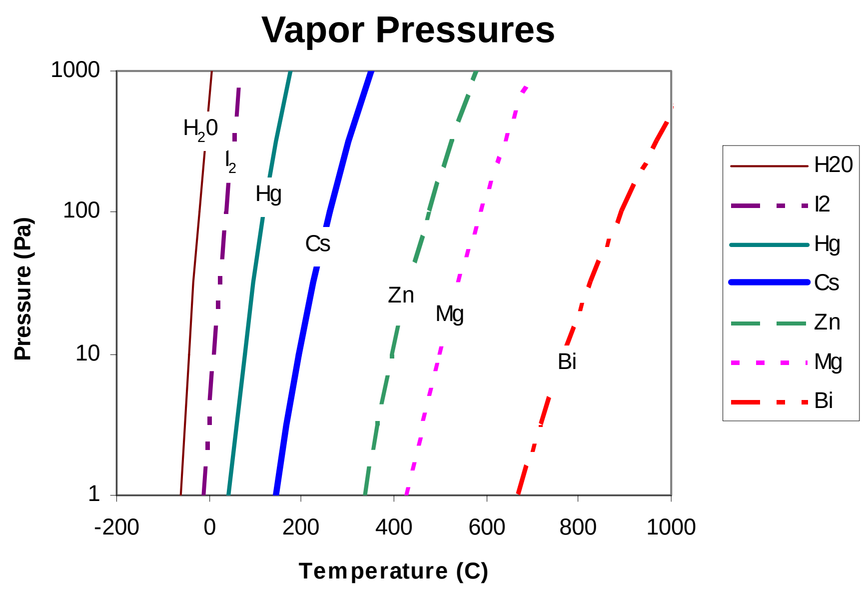
- Station keeping (15 years) ~ 0.75 km/s
- Earth to Mars (low thrust transfer) ~ 6 km/s

$$m_p / m_0 = 1 - \exp[-\Delta V / I_{sp} g_0]$$



HET Propellant Selection

- Factors to consider
  - Performance (thrust, Isp, eff.)
  - Density
  - Condensability/vapor pressure
  - Reactivity
  - Toxicity
  - Cost
  - Spacecraft interactions potential



Iodine vs. Cryogenic Noble Gases

- Cryogenic Kr stores at ~2.4 g/cc
  - Density = 2.41 g/c at b.p. (wikipedia)
- Cryogenic Xe stores at ~2.9 g/cc
  - Density = 3.06 at b.p. (wikipedia)
- Iodine stores at up to 4.9 g/cc at room temperature

Facility Background Pressure

- Indicated pressure is several times lower when running with iodine
- Sensitivity of pressure sensor to different gases is approximately proportional to ionization X-section at 150 eV.
- The ratio of I vs. I_2 *neutrals* is unknown at this time
- What can we say? Iodine partial pressure is roughly 50%-90% of what is indicated with the sensor calibrated for Xe
- Complicating matters is the presence of Xe (cathode) and other gases (N_2, etc.)

Gas	Ionization Cross Section at 150 eV (Ang^2)	Relative Sensitivity w.r.t. N_2	Relative Sensitivity w.r.t. Xe	Reported Relative Sensitivity w.r.t. N_2
N_2	1.75	1.00	0.40	
Kr	3.28	1.87	0.75	1.7 - 1.9
Xe	4.38	2.50	1.00	2.2 - 2.9
I	4.74	2.71	1.08	
I_2	8.48	4.85	1.94	5.4

Iodine Performance (BHT-200)

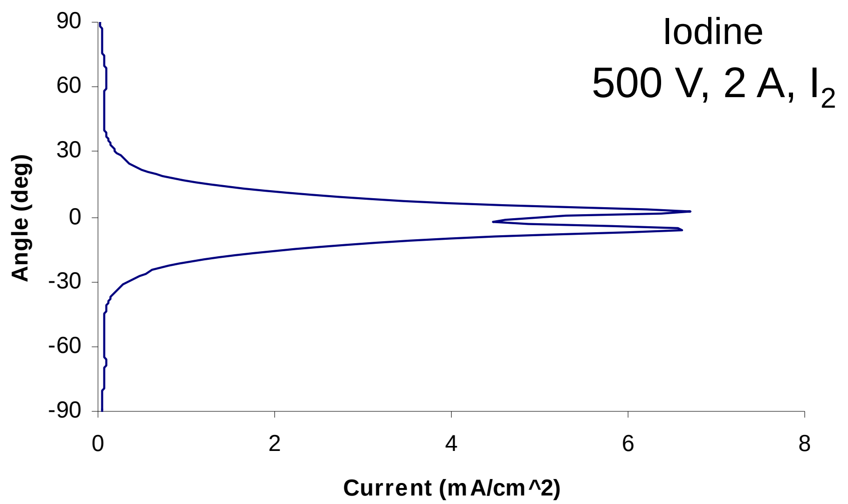
- Nominal thruster operating condition is 250 V, 200 W
  - Slightly higher T/P, slightly lower Isp

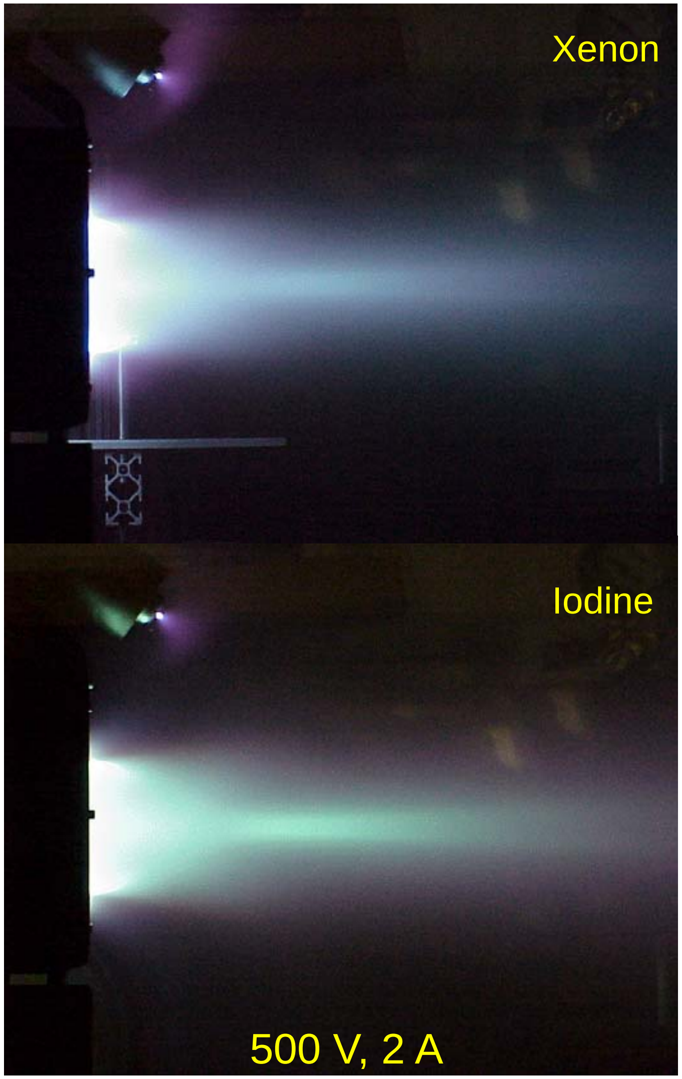
Gas	Flow Rate (mg/s)	Potential (V)	Current (A)	Power (W)	Thrust (mN)	T/P (mN/kW)	Anode Isp (s)	Anode Eff (-)
I2	1.02	151	1.02	155	11.1	71	1110	0.39
Xe	0.99	152	1.03	156	11.2	72	1151	0.41
I2	1.02	202	1.05	211	14.3	68	1436	0.48
Xe	0.99	202	1.01	203	13.5	67	1394	0.46
I2	0.62	251	0.53	133	8.3	62	1350	0.41
Xe	0.58	252	0.53	134	8.0	60	1409	0.41
I2	0.82	251	0.74	187	12.1	65	1506	0.48
Xe	0.78	252	0.76	193	11.9	62	1544	0.47
I2	0.85	302	0.81	245	14.4	59	1738	0.50
Xe	0.78	302	0.76	231	13.4	58	1750	0.50
I2	1.02	353	1.04	368	20.0	54	1996	0.53
Xe	1.04	353	1.13	400	19.4	48	1906	0.45

Szabo et al., "Performance Evaluation of an Iodine Vapor Hall Thruster", *AIAA Journal of Propulsion and Power*, Vol. 28, No. 4, July/August 2012.

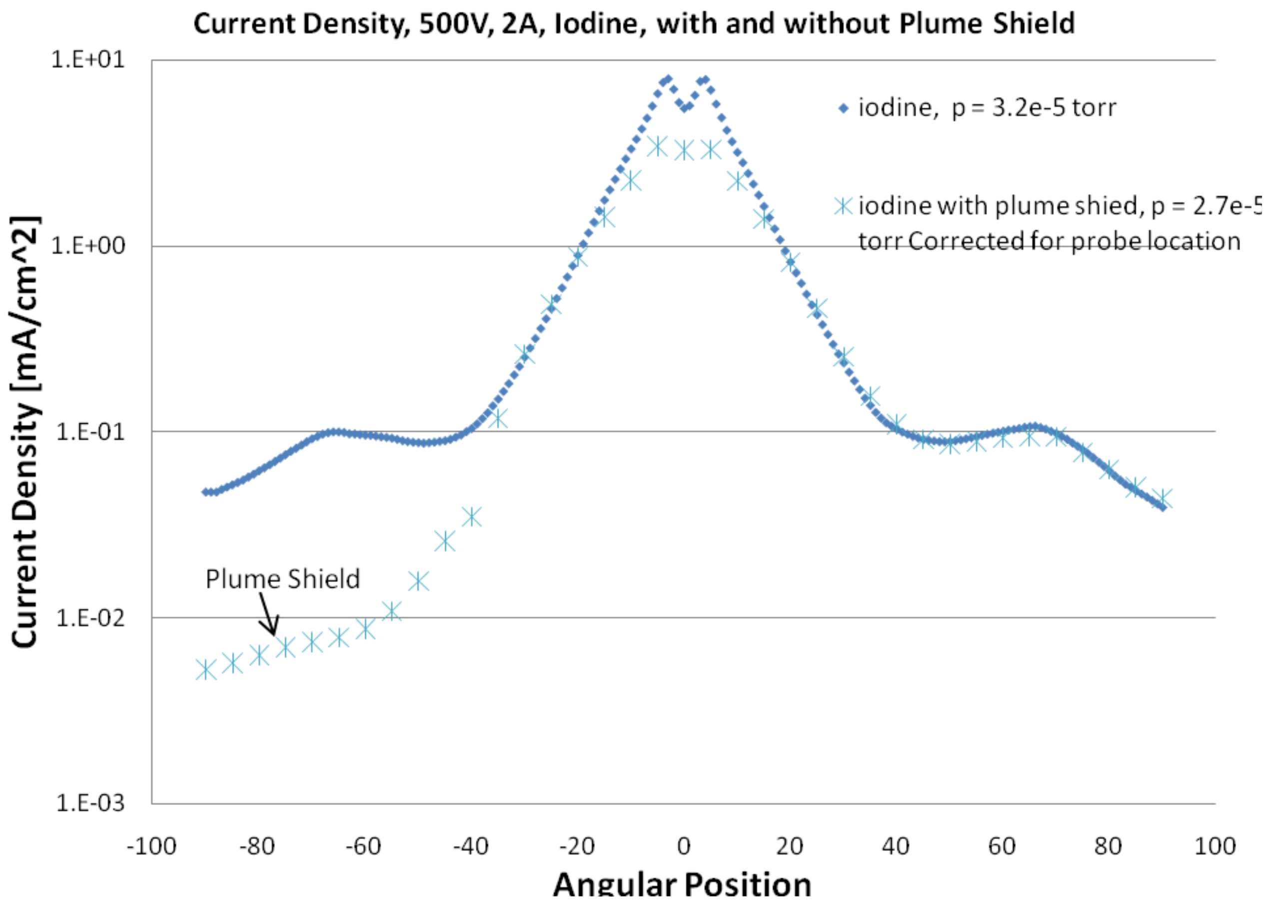
Iodine Plume (BHT-1000)

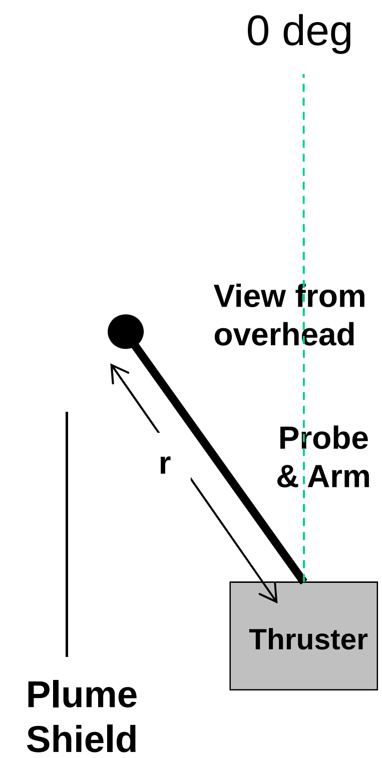
- Plume current (Faraday probe)
- Iodine yields lower divergence than Xe
- Favorable point for Xe
  - 30 degrees encloses 86% of Xenon plume, 90% of Iodine plume
- Tank pressure always lower with iodine





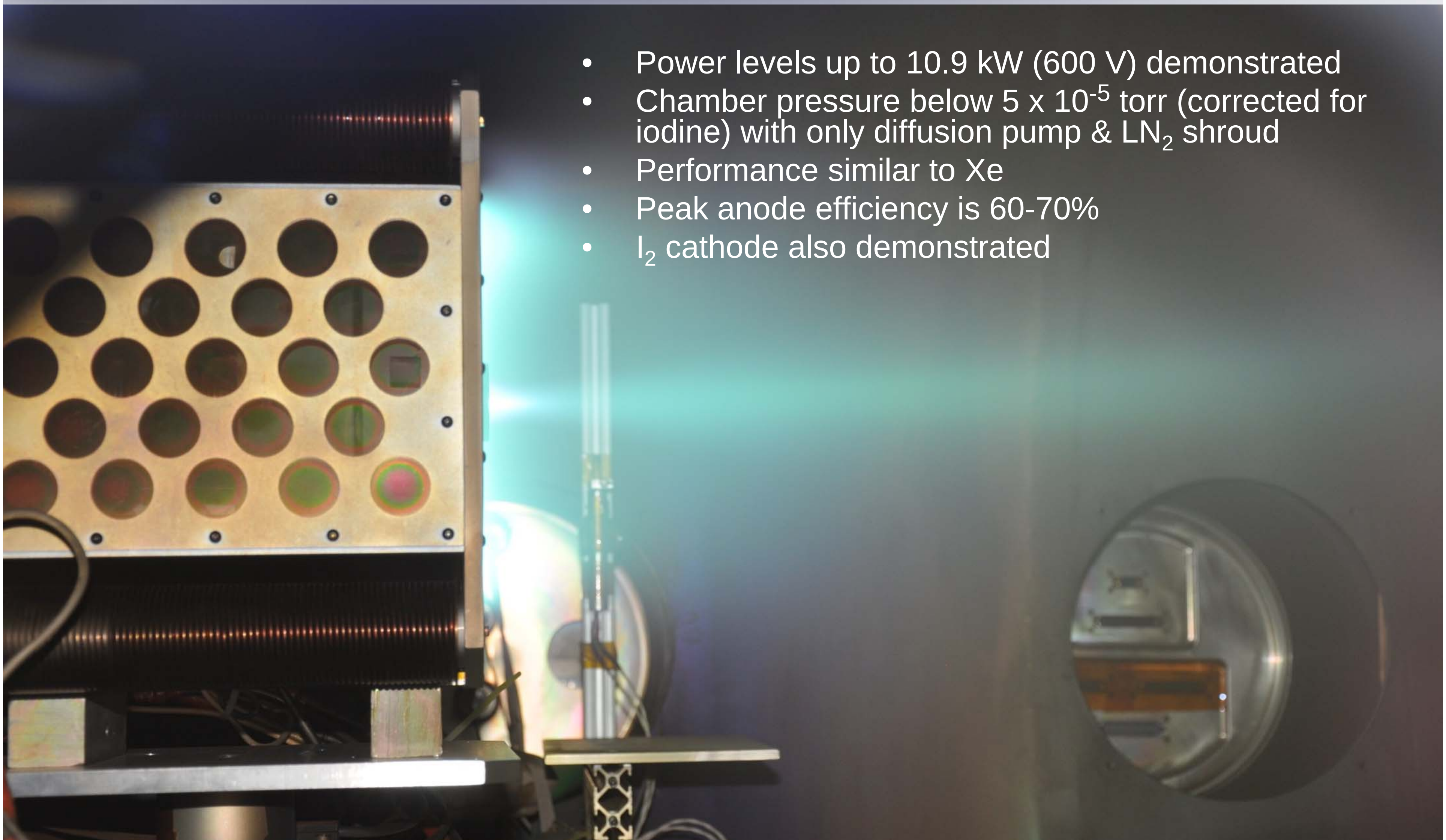
Plume Shield (BHT-1000)





A plume shield can greatly reduce the large angle plume

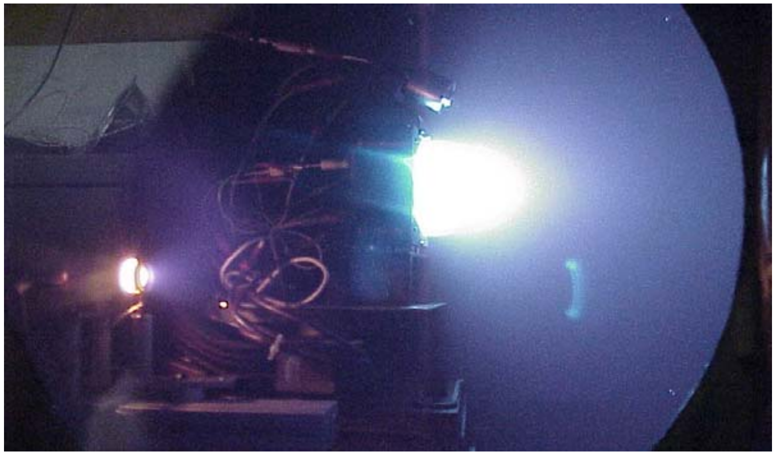
High Power Iodine Testing (BHT-8000)

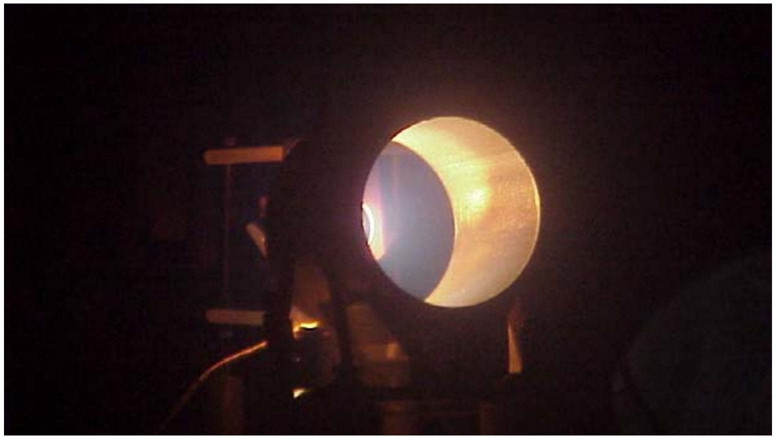


- Power levels up to 10.9 kW (600 V) demonstrated
- Chamber pressure below 5 x 10^{-5} torr (corrected for iodine) with only diffusion pump & LN_2 shroud
- Performance similar to Xe
- Peak anode efficiency is 60-70%
- I_2 cathode also demonstrated

Iodine Hollow Cathode (2012)

- Apparatus
  - Feedback controlled I_2 feed system
  - Busek LaB_6 cathode
- Key Results
  - Discharge initiation on LaB_6
  - Over 1 hour of operation on iodine
  - Additional 1/2 hour with thruster flowing Xe
  - Current up to ~50 A into anode





Presented at 2012 JPC

BUSEK Advanced Space Propulsion